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***Abstract*—Mobile network operators are confronted to an exponential growth of their traffic. One of the causes of this growth is the delivery of video services, including mobile television. Using a broadcast component like MBMS or DVB-H for the provision of the most popular mobile television channels can minimize their impact on the mobile network traffic. Such a component can also be investigated for other types of popular services and open the door to hybrid broadcast/unicast networks. The key factor for the efficiency of this approach is the choice of the services to be transmitted through the broadcast component. In this article, we introduce an energy criterion to make this choice. We use a simplified model of an hybrid network combining a DVB-T2 broadcast component to a LTE unicast component. Through the statistical study of the reception conditions of the users in this network, we evaluate the power gain brought by the use of the broadcast component for the delivery of a service as a function of the number of users that are using this service.**

I. Introduction

With the progressive disappearance of the analogue television throughout the world, large amounts of spectrum in the UHF and VHF bands are becoming available. This spectrum release, referred to as digital dividend, coincides with a tremendous growth in the area of mobile telecommunications. This motivates the assignment of the newly available frequencies to mobile oriented services. As it takes its origin from TV broadcasting, the most natural use of this spectrum is mobile TV. Unfortunately, the mobile TV sector struggles to find an economical model and many of the commercial offers that had been launched have eventually shut down. Hence in some countries, governments have auctioned some parts of the spectrum to mobile operators for additional 3G licenses.

A new idea for the exploitation of these frequencies is however emerging, consisting in a cooperation between cellular network and terrestrial broadcast network infrastructures in order to deliver other services than pure live TV programs to mobile devices ([1], [2]). The objective would be to reduce the multimedia unicast traffic on the cellular networks which has recently exploded with the use of smart phones and tablets. The cooperation would rely on a complementary exploitation of terrestrial digital TV transmitters to broadcast selected multimedia contents within a large coverage area. It would enable the off-load of some contents from one unicast network to a broadcast one.

The complementarity between unicast and broadcast modes has already been addressed by the last 3GPP-LTE specifications that define a broadcast component called E-MBMS (evolved multimedia broadcasting multicast service). E-MBMS can be activated in some situations to optimize the spectrum use in cellular networks ([3], [4]). Indeed, delivering identical pieces of data to different users in a unicast manner duplicates the bandwidth consumption and becomes a greedy strategy when the number of users increases within a cell. Meanwhile the broadcast approach provides service access to multiple users with a constant spectrum utilization. The dual unicast/broadcast modes of the 3GPP-LTE can be viewed as a cooperation between two virtual networks, however based on the same cellular infrastructure.

In this paper, we are interested in cooperative aspects between unicast and broadcast networks but considering different network topologies, namely the classical mobile cellular network based on small cells and the terrestrial TV broadcast network covering large areas with high power transmitters. Such a global hybrid network approach raises the question of how to decide which sub-network to exploit between the cellular unicast one and the terrestrial broadcast one, to deliver a service to a given number of end users. Many aspects can enter in consideration in the decision process and most of the already conducted studies focus on the transmission of live mobile TV services ([5],[6]). In that case, audience measurements provide a good criterion to decide which service has to be transmitted through the broadcast component. For other types of services, there is a lack of such a criterion.

In this study, we propose to investigate the problem under an energy point of view. Our goal is to find which one of the components or sub-network can deliver a service to the users with the smaller power consumption. In the sequel, we start in section II with the introduction of the energy criterion used for this study. In section III, we then present the model used for representing the hybrid network. Following this, we provide some mathematical derivations to give a closed form solution to the decision criteria. We finally present some practical results and interpretation before concluding.

II. Energy Criterion

In a hybrid network as previously introduced, a given service S can be transmitted through either the unicast component or the broadcast component. The choice of the component can be driven from energy considerations as proposed herein. For that purpose, let us express the amount of energy used to ensure the delivery of a time limited service, such as file transfer for instance. This writes,

$$\begin{aligned} E_S &= \textit{PSD} \times B_S \times T_S \\ &= \textit{PSD} \times \frac{Q_S}{\nu} \end{aligned} \tag{1}$$

where, E_S is the energy required to transmit service S in [J], *PSD* is the power spectral density level of the associated signal in [W/Hz], B_S is the bandwidth used to transmit the service in [Hz], T_S is the duration of the service transmission in [s], Q_S is the amount of data in [bit], and ν, in [bit/s/Hz], is the spectral efficiency used to ensure the transmission of the Q_S bits.

Note that (1) only holds for finite energy signals, i.e. time limited transmissions. In the case of a continuous service such as TV program provision, we rather have finite power signals. It is then convenient to use the following definition:

$$\begin{aligned} P_S &= \textit{PSD} \times B_S \times \tau_S \\ &= PSD \times \frac{R_S}{\nu} \end{aligned} \tag{2}$$

where P_S is the power required to transmit service S in [W], τ_S is the duty cycle of the service transmission, R_S is the data rate in [bit/s], and ν_S is the spectral efficiency associated to the transmission. Note that the duty cycle parameter is useful when considering a time segmented transmission of a continuous service.

Let us now consider two different transmission systems named A and B that could be associated to two different networks. It is interesting to define the energy or power gain obtained by using system B instead of system A to deliver service S. From (1) and (2), and because Q_S and D_S do not depend on the system but are only constrained by the service itself, it turns out that the energy gain is equivalent to the power gain, i.e.:

$$\begin{aligned} G_{A\rightarrow B} &= \frac{E_S^{(A)}}{E_S^{(B)}} = \frac{P_S^{(A)}}{P_S^{(B)}} \\ &= \frac{\textit{PSD}_A}{\textit{PSD}_B} \times \frac{\nu_B}{\nu_A} \end{aligned} \tag{3}$$

with ν_A and ν_B the spectral efficiencies reached by systems A and B, respectively.

The next step is to integrate the unicast or broadcast modes into the energy or power consumption evaluation. In the case of the transmission of a service to multiple users through a unicast system, the energy used is the sum of the energy used for all the users. This leads to:

$$E_S^{(U)} = PSD_U \times Q_S \times \sum_{k=1}^{N} \frac{1}{\nu_{U,k}} \tag{4}$$

with U indicating unicast mode and k being the user index $k \in [1 \cdots N]$.

In the case of a broadcast mode, things are very different since the energy to be used should be driven by the worst case user within the coverage area. Hence, the energy necessary to broadcast the service can be stated as:

$$E_S^{(B)} = PSD_B \times Q_S \times \max_{k\in[1;N]} \frac{1}{\nu_{B,k}} \tag{5}$$

with B denoting broadcast mode.

Using (4) and (5), we can finally express the gain obtained by transmitting a service over a broadcast component rather than over a unicast one:

$$G_{U\rightarrow B} = \underbrace{\frac{PSD_U}{PSD_B}}_{G_{P,U\rightarrow B}} \times \underbrace{\min_{k\in[1;N]} \nu_{B,k} \times \sum_{k=1}^{N} \frac{1}{\nu_{U,k}}}_{G_{R,U\rightarrow B}} \tag{6}$$

As mentioned before, a similar equation would have been obtained starting from (2) in the case of finite power signals. As evident from this equation, the energy gain can be separated into two parts. The former, related to the power levels exploited for the signal transmission, is denoted as $G_{P,u\rightarrow b}$. The latter, related to the spectral and temporal resources allocated to the service is denoted as $G_{R,u\rightarrow b}$.

In the sequel, the objective is to evaluate these gains for a given topology of the hybrid network. In that perspective, the next section introduces the proposed hybrid unicast/broadcast network model.

III. Hybrid Network Model

The proposed hybrid network consists of a broadcasting network with a large coverage area that overlaps the multiple cells of a unicast network. As depicted in Fig. 1, the broadcasting coverage area is modeled by one circular cell and the unicast coverage area results from adjacent smaller hexagonal cells.

From this model, we need to derive the Probability Density Function (PDF) of the distance D between a given transmitter (broadcast or unicast) and any receiver located in the hybrid coverage area. To that end, we assume a uniform distribution of the users across the area. Classical derivations based on the geometrical properties of the hybrid coverage model are then used to obtain the PDF.

In the broadcast case, considering a circular geometry, it is straightforwardly obtained that:

$$\textit{PDF}_B(D) = \frac{2D}{R^2} \tag{7}$$

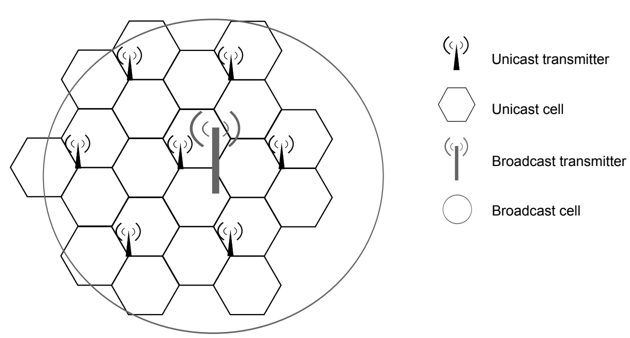

Fig. 1. Proposed hybrid unicast/broadcast network

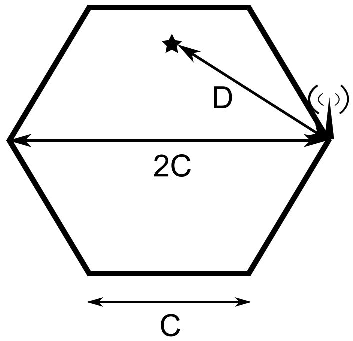

Fig. 2. Distance D between the transmitter and one receiver in an hexagonal cell

with R the radius of the circle representing the coverage area.

In the unicast case, the PDF derivation is trickier due to the particular shape of the coverage area as depicted in Fig. 2. Taking into consideration such an hexagonal geometry, and after some manipulations, it can be shown that the PDF of the distance D writes:

$$\textit{PDF}_U(D) = \begin{cases} \frac{2\pi \times D}{3 \times A} & \text{for } D < C, \\ \frac{2D \times sin^{-1}\left(\frac{\sqrt{3}C}{2D}\right)}{A} & \text{for } C < D < \sqrt{3}C, \\ \frac{2D \times \left(sin^{-1}\left(\frac{\sqrt{3}C}{D}\right) - \frac{\pi}{3}\right)}{A} & \text{for } \sqrt{3}C < D < 2C. \end{cases} \tag{8}$$

where A is the area of the hexagon, that is:

$$A = \frac{3\sqrt{3}}{2} \times C^2 \tag{9}$$

with C the side length of the hexagon. This PDF is illustrated in Fig. 3 and it clearly appears that it does not follow a linear shape when $D > C$.

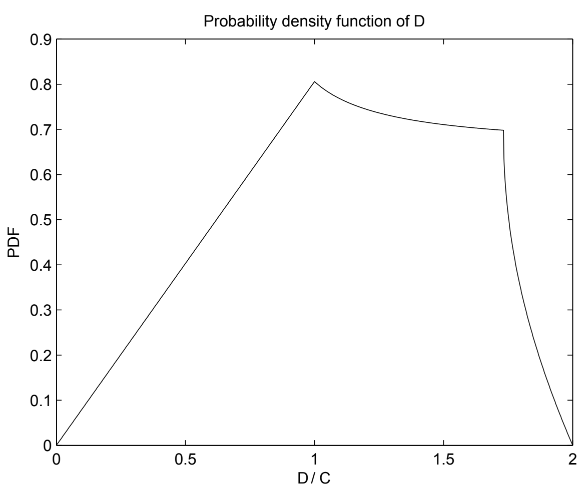

Fig. 3. Probability density function of distance D in an hexagonal cell

IV. Evaluation of the power gain

We have now to integrate path loss attenuations into the coverage model in order to obtain the power gain $G_{G,U \to B}$ introduced in (6). Hence, let L be the power attenuation caused by the distance D between the transmitter and the receiver. This is commonly expressed as:

$$L(D) = \left(\frac{\lambda}{4\pi \times D}\right)^{\alpha} \tag{10}$$

Let $\textit{SNR}_{min}(\nu_i)$ be the minimal value of signal to noise ratio that is required to guarantee a reliable reception for a signal which transmission is carried out at a spectral efficiency ν_i. Note that ν_i results for instance from the combined used of a given modulation order and a given channel coding rate. We will consider ν_1 as being the smaller spectral efficiency that can be used.

Besides, let us make the two following assumptions:

- The radio frequency (RF) front ends of the receivers have similar performances, be it for unicast reception or broadcast reception, even if not operating in the same RF bands. This implies that the same received power leads to the same SNR at the input of the base band processing;
- Both unicast and broadcast networks have been designed in order to achieve $SNR_{min}(\nu_1)$ onto the border of the cells. This means that the transmitted power is such that the minimal SNR required for minimal spectral efficiency ν_1 is guaranteed at the boundaries of the coverage area.

From these assumptions, the evaluation of the power gain can easily be stated as:

$$G_{P,U \to B} = \frac{\textit{PSD}_B}{\textit{PSD}_U} = \frac{L_U(D_{U,max})}{L_B(D_{B,max})} \times \frac{\textit{SNR}^{(B)}_{min}(\nu_1)}{\textit{SNR}^{(U)}_{min}(\nu_1)} \tag{11}$$

where $L_U(D_{U,max})$ (resp. $L_B(D_{B,max})$) denotes the power attenuation experienced in the unicast (resp. broadcast) network at the maximal distance to the transmitter $D_{U,max}$ (resp. $D_{B,max}$). For the network topology considered herein, we have for example $D_{U,max} = 2C$ and $D_{B,max} = R$. Note that $L_U(D)$ can be different from $L_B(D)$, even with equal distance D, since λ and α may not be the same in broadcast and unicast situations.

V. Evaluation of the resource gain

From (6), resource gain G_R depends on the spectral efficiencies that users can reach through the unicast or the broadcast components. Thus, we need to derive the PDF of the attainable spectral efficiency $\textit{PDF}(\nu)$ for all locations in the hybrid network. In a second step, it will then be possible to obtain the PDF of the resource gain G_R that can be expected within the hybrid network.

A. PDF of the attainable spectral efficiency

Let first $D_{U,i}$ (resp. $D_{B,i}$) be the distance at which reliable reception is possible for a spectral efficiency ν_i. We can actually write:

$$\frac{L(D_{U,i})}{L(D_{U,max})} = \frac{SNR^{(U)}_{min}(\nu_i)}{SNR^{(U)}_{min}(\nu_1)} \tag{12}$$

and similarly in the broadcast case. Using (10) finally gives

$$D_{U,i} = e^{\frac{1}{\alpha}\ln\left(\frac{SNR^{(U)}_{min}(\nu_i)D^{\alpha}_{U,max}}{SNR^{(U)}_{min}(\nu_1)}\right)} \tag{13}$$

This last result allows us to compute the probability P_i that a given user as the chance to benefit from a spectral efficiency ν_i. This actually writes as:

$$P_{U,i} = P_U(\nu = \nu_i) = \int_{D_{U,i}}^{D_{U,i+1}} \textit{\textbf{PDF}}_U(D)dD \tag{14}$$

and similarly for $P_{B,i}$. Finally, the PDF of ν can be expressed as:

$$\textit{\textbf{PDF}}_U(\nu) = \sum_{i}^{M} P_{U,i} \times \delta(\nu - \nu_i) \tag{15}$$

and similarly for $\textit{\textbf{PDF}}_B$, with M the number of available spectral efficiencies.

To illustrate this for the unicast component, let us extract SNR_{min} and ν_i values from the 3GPP-LTE specifications [7], as listed in Table I. The corresponding $\textit{\textbf{PDF}}_U(\nu)$ using $\alpha = 3$, $F_p = 2.6GHz$, and $C = 1km$ has been computed and is depicted in Fig. 4.

In the same way, the PDF of the broadcast component can be exemplified on the basis of DVB-T2 specifications [8]. The related SNR_{min} and ν_i values are reported in Table II. Choosing $\alpha = 2.5$, $F_p = 800MHz$ and $R = 100km$ we obtain the $\textit{\textbf{PDF}}_B(\nu)$ plotted Fig. 5.

B. PDF of resource gain

We first define $C_U(N)$ as the resource related part of the cost of the unicast transmission for N users:

$$C_U(N) = \sum_{k=1}^{N} \frac{1}{\nu_{U,k}} \tag{16}$$

Denoting C_0 the cost $C_U(N)$ for $N = 1$, the Probability Density Function of C_0 is

$$\textit{\textbf{PDF}}(C_0) = \sum_{i=1}^{M} P_i \times \delta(C_0 - \frac{1}{\nu_i}) \tag{17}$$

index	SNR_{min}	ν
1	-7	0.1523
2	-5	0.2344
3	-3	0.3770
4	-1	0.6016
5	1	0.8770
6	2.5	1.1758
7	4.5	1.4766
8	6.5	1.9141
9	8.5	2.4063
10	10	2.7305
11	12	3.3223
12	14	3.9023
13	16	4.5234
14	18	5.1152
15	20	5.5547

TABLE I
SPECTRAL EFFICIENCIES VERSUS SNR FOR LTE

index	SNR_{min}	ν
1	2.0	0.87
2	4.1	1.18
3	5.3	1.31
4	6.6	1.45
5	6.9	1.74
6	9.6	2.36
7	11.0	2.60
8	12.8	2.89
9	13.9	3.07
10	14.4	3.54
11	16.1	3.94
12	18.2	4.34
13	19.0	4.72
14	20.5	5.25
15	22.9	5.78
16	24.5	6.14
17	25.8	6.49

TABLE II
SPECTRAL EFFICIENCIES VERSUS SNR FOR DVB-T2

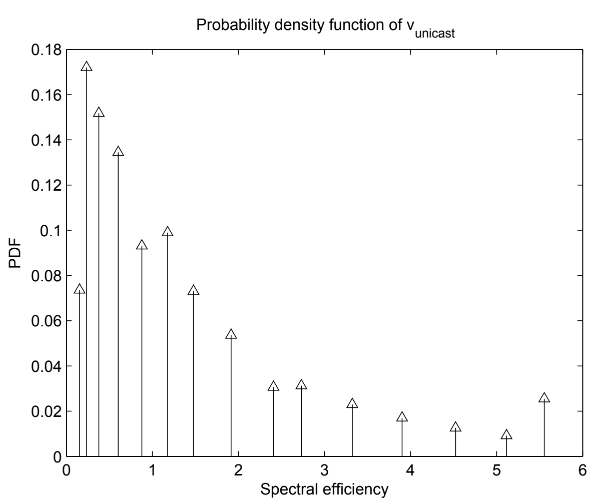

Fig. 4. Probability density function of spectral efficiencies for unicast

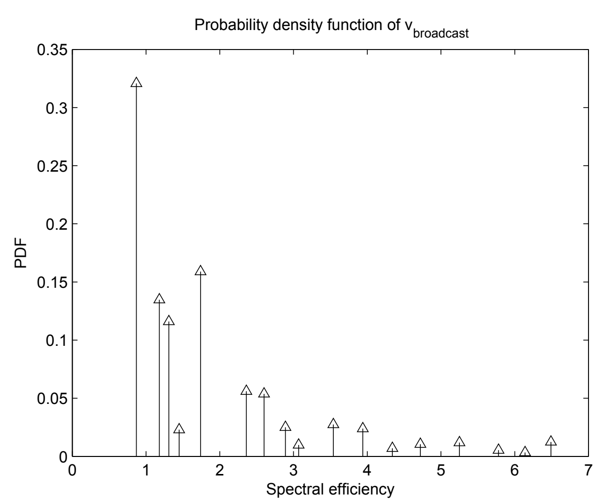

Fig. 5. Probability density function of spectral efficiencies for broadcast

For any other value of N, the PDF becomes:

$$\textit{PDF}(C_U) = \underbrace{\textit{PDF}(C_0) \star \textit{PDF}(C_0) \star ... \star \textit{PDF}(C_0)}_{\text{N times}} \quad (18)$$

Computing these N successive convolutions leads to the following result:

$$\textit{PDF}(C_U) = \sum_{k=1}^{\Gamma_M^N} P_k \times \delta(C_U - C_{U,k}) \quad (19)$$

where Γ_M^N is the number of N-combinations from a set of M elements with repetition.

As the number of elements of this PDF rapidly increases with the number N of users, an approximation can be proposed to get a closed form expression to this PDF. In particular, compared with the exact PDF obtained through numerical computing and with the PDF obtained by Monte Carlo simulations for greater numbers of users, the Nakagami distribution turns out to be a good approximation. This can be expressed as:

$$\textit{PDF}(C_U) \approx \frac{2\mu^\mu}{\Gamma(\mu)\omega^\mu} C_U^{2\mu-1} e^{-\frac{\mu}{\omega}C_U^2} \quad (20)$$

with μ and ω being,

$$\mu = \frac{E^2[C_U^2]}{Var[C_U^2]} \quad (21)$$

and,

$$\omega = E[C_u^2]. \quad (22)$$

$E[C_U^2]$ and $Var[C_U^2]$ can be expressed as polynomials of N with coefficients being linear combinations of statistical moments of C_0, that is:

$$E[C_U^2] = N^2E^2[C_0] + N \times Var[C_0] \quad (23)$$

and

$$\begin{aligned} Var[C_U^2] =& (4Var[C_0]E^2[C_0])N^3 \quad (24)\\ &+ (2Var^2[C_0] + 4E[C_0]E[(E[C_0] - C_0)^3])N^2\\ &+ (E[(E[C_0] - C_0)^4] - 3Var^2[C_0])N \end{aligned}$$

To validate this approximation, Fig. 6 gives the theoretical PDF of C_u for $N = 16$ users and the estimated one obtained using the Nakagami distribution.

As done for the unicast component of the system, let us now define the partial cost $C_B(N)$ for the broadcast component:

$$C_B(N) = \max_{k\in[1;N]} \frac{1}{\nu_{B,k}} \quad (25)$$

Let ν_{min} be the smallest ν_i allowing a proper reception of the broadcast signal for all the N users. The probability for ν_{min} to be greater than a given ν_i is:

$$P_{sup,i} = P(\nu_{min} > \nu_i) = \left(\sum_{k=i+1}^{M} P_{B,k}\right)^N \quad (26)$$

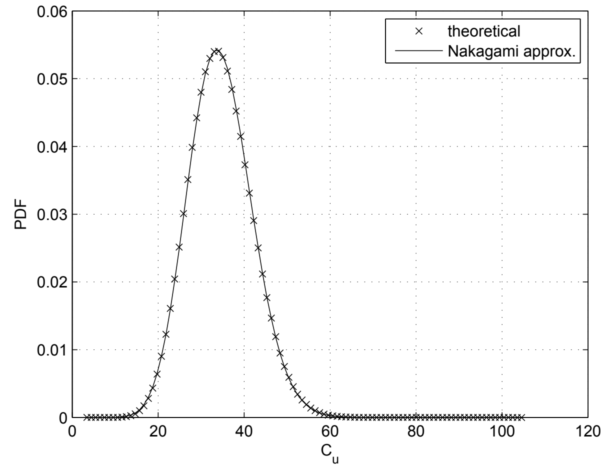

Fig. 6. Theoretical probability density function of C_U for 16 users versus Nakagami estimate

where P_i is the probability already defined in (14). Then the probability for ν_{min} to be equal to a given ν_i is:

$$P_{min,i} = P(\nu_{min} = \nu_i) = 1 - P_{sup,i} - \sum_{l=1}^{i-1} P_{min,l} \quad (27)$$

and the expression of the PDF of C_B writes:

$$\textit{PDF}(C_B) = \sum_{i=1}^{M} P_{min,i} \times \delta\left(C_B - \frac{1}{\nu_i}\right) \quad (28)$$

Finally, from (20) and 28 we can easily obtain the closed form for the PDF of the resource related part of the gain:

$$\begin{aligned} \textit{PDF}(G_{R,U\to B}) =& \sum_{i=1}^{M} P_{min,i} \times \frac{2\mu^\mu}{\Gamma(\mu)\omega^\mu}\\ & \times (C_U \times \nu_i)^{2\mu-1} e^{-\frac{\mu}{\omega}(C_U\times\nu_i)^2} \quad (29) \end{aligned}$$

VI. RESULTS

Fig. 7 gives the evolution of the global gain $G_{U\to B}$, which correspond to the broadcast gain over unicast, when the total number N of users changes within the proposed hybrid network. Results are obtained according to the parameters listed in Table III and using the spectral efficiency tables introduced before (see Table II and I). Simulations results are obtained by direct numerical computation of the global gain $G_{U\to B}$ of (6) through uniform random locations of the N users. From these computations, curves corresponding to "average", "minimum" and "maximum" cases are reported in the figure. The theoretical results are the average gains obtained with the proposed Nakagami approximation.

We first note that these results validate the use of the Nakagami distribution as an approximation of the PDF of the resource related part of the unicast cost. Then, it turns out that an average gain of 0dB is obtained when 5.0×10^3 users are active. This value represents the threshold that could drive the off-load of traffic from the unicast to the broadcast component

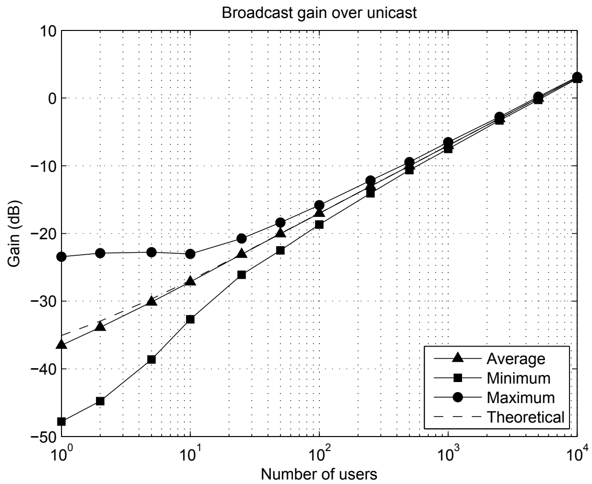

Fig. 7. Analytical results and simulations

Parameter	**Broadcast**	**Unicast**
α	2.5	3
Frequency	800MHz	2.6GHz
Cell radius	100km	1km
User distribution	uniform	

TABLE III
SIMULATION PARAMETERS

of the hybrid network. This value can seem quite high, but recall that in the studied system, the area of the broadcast cell is 12.1×10^3 times greater than the area of a unicast cell (see Table III). This means that the threshold eventually represent an average of 0.42 user per unicast cell, which correspond to less than 1 user every 2 cells.

In other words, from energy considerations, the use of the large scale broadcast component is more favourable than the small scale unicast one as soon as one half of the unicast cells are requested for the same service delivery. This tends to prove that an hybrid unicast/broadcast coverage approach would allow global energy consumption reduction. In comparison, LTE-EMBMS-like systems are more flexible, allowing the switch from unicast to broadcast component cell by cell, but need that at least 2 users in the same cell use the same service for this switch to have an interest.

VII. CONCLUSIONS

Using a simplified model of an hybrid unicast/broadcast network we have proposed a criterion to adequately select which one of the components is better suited for the transmission of a given service. We have derived the theoretical aspects for the energy gain computation and proposed a closed form for the PDF of this gain based on the Nakagami distribution.

Our simulation results show that, from an energy point of view, a DVB-T2 broadcast system is more efficient than a LTE unicast system with less than 0.5 user per cell.

Future extensions of this work will be the integration of a more realistic model of the network, including a non uniform distribution of the users and heterogeneous sizes for the unicast cells. We will also perform further comparisons with other hybrid topologies like MBMS or MB-SFN.

ACKNOWLEDGMENTS

The authors would like to thank the French ANR project ”$M3$” (Mobile Multi Media) and the European CELTIC project “ENGINES” (Enabling Next GeneratIon NEtworks for broadcast Services) for their support of this work.

REFERENCES

[1] www.tdf.fr/assets/files/upload/Presse/Projet_B2M_141211.pdf
[2] https://m3.rd.francetelecom.com/espace-public
[3] Technical Specification Group Services and System Aspects, “Multimedia Broadcast/Multicast Service (MBMS); Architecture and functional description,” 3rd Generation Partnership Project (3GPP), Tech. Rep. TS 23.246 Version 11.1.0, March 2012
[4] Technical Specification Group Radio Access Network, “Evolved Universal Terrestrial Radio Access Network (E-UTRAN); General aspects and principles for interfaces supporting Multimedia Broadcast Multicast Service (MBMS) within E-UTRAN,” 3rd Generation Partnership Project (3GPP), Tech. Rep.36.244 Version 10.2.0, September 2011
[5] D. Catrein, J. Huschke, and U. Horn, “Analytic Evaluation of a Hybrid Broadcast-Unicast TV Offering,” Vehicular Technology Conference (VTC Spring 2008), May 2008.
[6] P. Unger, and T. Kürner, “Radio network planning of DVB-H/UMTS hybrid mobile communication network,” European Transactions on Telecommunications, Volume 17, Issue 2, pages 193-201, March/April 2006.
[7] C. Mehlfhrer, M. Wrulich, J.C. Ikuno, D. Bosanska, and M. Rupp, “Simulating the Long Term Evolution Physical Layer,” Proceedings of 17th European Signal Processing Conference (EUSIPCO 2009), Scotland, Glasgow, August 2009.
[8] ETSI TR 102 831, “Digital Video Broadcasting (DVB); Implementation guidelines for a second generation digital terrestrial television broadcasting system(DVB-T2)”